

Narrow deeply bound K^- atomic states

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Abstract

Using optical potentials fitted to a comprehensive set of strong interaction level shifts and widths in K^- atoms, we predict that the K^- atomic levels which are inaccessible in the atomic cascade process are generally narrow, spanning a range of widths about 50 - 1500 keV over the entire periodic table. The mechanism for this narrowing is different from the mechanism for narrowing of pionic atom levels. Examples of such ‘deeply bound’ K^- atomic states are given, showing that in many cases these states should be reasonably well resolved. Several reactions which could be used to form these ‘deeply bound’ states are mentioned. Narrow deeply bound states are expected also in \bar{p} atoms.

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The strong interaction level shifts and widths in hadronic atoms provide valuable information on the hadron-nucleus interaction at threshold [1]. Radiative transitions seen in a typical X-ray spectrum normally terminate at a circular atomic level ($n = l + 1, l$) having a nonradiative, absorptive width of order 1-10 keV. Lower atomic levels which are inaccessible via the atomic cascade process are expected to be considerably broader, judging by the 2 - 3 orders of magnitude increase in width going from $(n + 1, l + 1)$ to (n, l) . The interest in observing such ‘deeply bound’ atomic levels stems from anticipating a larger overlap of the corresponding wave functions with the nuclear density profile, and hence a greater sensitivity to the hadron-nucleus strong interaction. However, once the width becomes of order 1 MeV, it should be increasingly difficult to resolve these levels.

Todate, deeply bound hadronic atom levels have been directly observed only for pions [2,3], using the $(d, {}^3\text{He})$ recoilless reaction [4] on ${}^{208}\text{Pb}$, following earlier predictions that the $1s$ and $2p$ atomic levels in pionic Pb have widths of order 0.5 MeV, significantly less than the approximately 1.5 MeV spacing [5,6]. This striking narrowness is due to the well established repulsive s -wave part of the pion-nucleus potential at threshold which pushes the corresponding atomic wave functions out of the nucleus such that their overlap with the nucleus, and hence with the imaginary part of the potential, is substantially reduced. A similar, but not as favourable situation might occur for Σ^- atoms due to the inner repulsion of the Σ nucleus potential [7–9]. The other hadronic atom species which have been studied experimentally, consisting of K^- and \bar{p} atoms, do not appear at first sight likely candidates for narrow deeply bound states, since the real part of the hadron-nucleus potential at threshold is known for these hadronic species to be strongly attractive and, furthermore, the imaginary (absorptive) part is particularly strong, reaching (absolute) values of order 50 - 100 MeV inside nuclei [1]. These features of the K^- -nucleus optical potential V_{opt} follow qualitatively from various microscopic studies of V_{opt} utilizing the dominant effect of the $\Lambda(1405)$ subthreshold unstable bound state [10–17].

In this Letter we wish to point out, for strongly absorptive potentials, a *new* mechanism for suppressing the widths of deeply bound atomic states. It is based on the observation made by Krell long time ago [18] that absorptive potentials generate effective repulsion which pushes the wave function further outside the nucleus. We demonstrate this effect for *realistic* K^- nucleus optical potentials obtained by fitting to a comprehensive set of K^- atomic levels reached in atomic cascade, as deduced from K^- X-ray spectra. Thus, we predict that K^- deeply bound atomic states, generally, are remarkably narrow and, therefore, warrant experimental study.

The interaction of the K^- meson at threshold with the nucleus is described by the Klein-Gordon equation of the form:

$$\left[\nabla^2 - 2\mu(B + V_{opt} + V_c) + (V_c + B)^2 \right] \psi = 0 \quad (\hbar = c = 1) \quad (1)$$

where μ is the K^- - nucleus reduced mass, B is the complex binding energy and V_c is the Coulomb interaction of the K^- with the nucleus. Only the leading term in V_{opt} is retained in Eq. (1). We have checked that this neglect is well justified for atomic states. The phenomenological density dependent (DD) potential of Friedman *et al.* [19,20] which generalizes and updates Batty’s earlier analysis [21] is given by:

$$2\mu V_{opt}(r) = -4\pi \left(1 + \frac{\mu}{m} \right) b(\rho) \rho(r) \quad , \quad (2)$$

$$b(\rho) = b_0 + B_0 \left(\frac{\rho(r)}{\rho_0} \right)^\alpha, \quad (3)$$

where b_0 and B_0 are complex parameters determined from fits to the data, m is the mass of the nucleon and $\rho(r)$ is the nuclear density distribution normalized to the number of nucleons A , and $\rho_0 = 0.16 \text{ fm}^{-3}$ is a typical central nuclear density. ‘Macroscopic’ nuclear densities [1] were used in most of the present calculations. For a detailed discussion of the DD potentials as well as of the χ^2 fits to the kaonic atom data see Ref. [1]. Here we note only that the full data base for kaonic atoms, containing 65 data points over the whole of the periodic table, was used in the fits, which yielded χ^2 per point around 1.6, representing good fits to the data. In this work, in order to test the dependence of our predictions on the type of fitted potentials, we use two potentials of Table 6 in Ref. [1]. The first potential is of a $t\rho$ form ($b_0 = 0.62 + i0.92 \text{ fm}$, $B_0 = 0$) with depths of about 70 MeV for the (attractive) real part and 110 MeV for the (absorptive) imaginary part. The second potential is of a DD form satisfying the low density limit (with b_0 given by the K^-N scattering amplitude at threshold in free space). Its parameters ($b_0 = -0.15 + i0.62 \text{ fm}$ and $B_0 = 1.66 - i0.04 \text{ fm}$, $\alpha = 0.24$) produce a considerably stronger attraction in the nuclear interior, but weaker absorptivity than for the $t\rho$ potential. Both give a good account of the K^- atomic data with the DD potential yielding a significantly better fit. Parameters for the density distributions $\rho(r)$ are given in Table 2 of Ref. [20].

We begin the discussion with the $1s$ atomic state in kaonic carbon where a width of 62 keV is calculated together with a binding energy of 270 keV, which makes this level resolved from the observed 2 keV broad $2p$ atomic level bound by 111 keV. Figure 1 shows the absolute value squared of the radial wave function of the $1s$ state. The dashed curve is for the Coulomb interaction due to the (finite size) nuclear charge distribution and including also the usual vacuum polarization terms. The other curves include additional components of the $t\rho$ potential, as obtained from fits to kaonic atom data. The solid line is for the full complex $t\rho$ potential added, the dotted line is for adding only its imaginary part, and the dashed-dot curve is for adding only its real part. The results are almost indistinguishable if the DD potential is used instead. A striking difference compared to pionic atoms [5,6] is immediately clear from this figure, namely, that the strong interaction effects are completely dominated by the imaginary potential. The strength of the imaginary potential is such that the wave function is effectively excluded from the nuclear interior ($r \lesssim 3 \text{ fm}$), and the addition of the *attractive* real potential has a negligible effect on the wave function. This repulsion reduces sufficiently the overlap with the nucleus, and hence with $\text{Im } V_{opt}$, such that the width of the $1s$ state becomes 50 times smaller than would have been the case for the Coulomb wave function (3.1 MeV).

A comment on the dash-dot curve in Fig. 1 showing the wave function for $\text{Im } V_{opt}=0$ is in order. This wave function displays *repulsion* with respect to the Coulomb wave function shown by the dashed curve, even though $\text{Re } V_{opt}$ is *attractive*. This phenomenon occurs in hadronic atoms whenever $\text{Re } V_{opt}$ is deep enough to bind *nuclear* states ([18]; see also [22]). Since the real *atomic* wave function is orthogonal to the wave functions of these deeper states, it develops nodes inside the nucleus. Such a node is seen in Fig. 1. These extra nodes, and the actual l -value, determine the position of the main peak of the atomic wave function, which in the present case occurs further out than the peak of the Coulomb wave function, signifying repulsion. When $\text{Im } V_{opt}$ is switched on to its full strength, it is clear

from Fig. 1 that the K^- wave function gets thoroughly suppressed in the nucleus. This suppression depends weakly on $\text{Re } V_{\text{opt}}$, which means that for strongly absorptive potentials the nuclear states affect marginally the atomic states.

The phenomenon of well resolved deeply bound atomic states is not confined to light kaonic atoms but is universal all over the periodic table. Figure 2 shows the calculated ‘deeply bound’ portion of the K^- atomic spectrum in Ni as a typical medium weight nucleus and Fig. 3 shows similar results for Pb. For these $N > Z$ nuclei we have used neutron densities that slightly extend beyond those for protons, with $R_n - R_p = 0.20$ fm for Ni and 0.36 fm for Pb, where R_n and R_p are the half density radius parameters. In both examples one sees many deep atomic levels whose widths are less than 1 MeV. Although some overlap is observed in the case of heavy nuclei, we note that by using l -selective reactions to populate such states certain levels could be expected to be reasonably well resolved.

Further insight into the mechanism responsible for the width suppression is provided by Fig. 4, showing strong interaction widths and shifts for the $5g$ level in kaonic Pb calculated as a function of $\text{Im } b_0$ for the $t\rho$ potential. The solid curves are for the full complex optical potential V_{opt} , whereas the dashed curves are for the imaginary part of the optical potential only ($\text{Re } b_0 = 0$). The real V_c potential is included, of course, in all cases. For small values of $\text{Im } b_0$, the effect of the attractive $\text{Re } V_{\text{opt}}$ is to increase the width by roughly a factor of 8 with respect to that calculated when $\text{Re } V_{\text{opt}}$ is switched off. It is remarkable, however, that in each of these cases the width saturates such that the difference between the two calculated widths becomes less than 50%. This saturation and near equality of the calculated widths for the nominal value of $\text{Im } b_0$ is observed for other deeply bound states with different values of l , regardless of whether the solid curve for Γ lies above the dashed curve for Γ (as in Fig. 4) or below it (as is the case, for example, for the $4f$ state in Pb and for the $1s$ state in C discussed in connection to Fig. 1). For the dashed curve, it is seen that the width saturates already at about 15% of the nominal value of $\text{Im } b_0$, a feature which is due to the exclusion of the wave function from the nuclear interior. The shift in this case (with $\text{Re } b_0 = 0$) is repulsive. When the attractive $\text{Re } V_{\text{opt}}$ is included, the (solid curve) width reaches a maximum at as little as 7% of the nominal depth and then begins to decrease. That is accompanied initially by a fairly constant repulsive shift which eventually goes down, remaining nevertheless repulsive. We recall that a repulsive shift due to an *attractive* real optical potential indicates the existence of deeply bound *nuclear* states [22]. These states, for the nominal value of $\text{Im } b_0$, are very broad (Γ of order 50 MeV and more) and are not expected to be seen as well defined states.

In order to check the sensitivity of the results to variations in the model, we have replaced the $t\rho$ optical potential by the DD potential and found that although the spectrum of the deeply bound nuclear states varies considerably, the overall picture regarding the *atomic* states remains essentially unchanged. For example, the widths of the circular $l=1\dots 5$ levels in Pb change by less than 5% when the DD potential is used. Similar changes are observed in the calculated widths when the macroscopic densities are replaced by single particle densities (see Ref. [1]). The positions of the above levels change by less than 12 keV. The largest sensitivity to the potential used and to the type of nuclear density is observed for the binding energy of the $1s$ level, where the variation is up to 40 keV, being however only 2.5% of the width of the level. We point out that the extrapolation from the atomic states observed in the atomic cascade process, to the ‘deeply bound’ atomic states, involves 6 MeV at most

for Pb, and that no strong model dependence is expected over such an energy interval. In contrast, the location of the very deep and broad *nuclear* states depends sensitively on the V_{opt} used.

Before closing, we wish to mention a few candidate reactions to form K^- ‘deeply bound’ atomic states. The lesson gained from searching for such π^- states [2–4] is that a particularly low momentum transfer in the forward direction, say $q \lesssim 50$ MeV/c, is necessary in order to achieve good angular momentum selectivity ($\Delta l \sim qR$) and to minimize the suppressive effects of the nuclear distortion. This calls for using as low-energy K^- beam as possible, short of using stopped K^- . At the AGS, however, the momentum transfer in the reaction (K^-, p) for example, with a typical K^- incident momentum $p_L = 600$ MeV/c and for protons emitted in the forward direction, is already too large to be useful ($q \sim 180$ MeV/c). Particularly low-energy K^- , of kinetic energy $T_{K^-} = 16$ MeV, can be produced in the decay at rest of the $\phi(1020)$ meson. The corresponding momentum transfer in the in-flight reaction (K^-, p) , $q \sim 50$ MeV/c, is sufficiently small in this case, by far smaller for example than the value $q \sim 110$ MeV/c for the reaction (K^-, γ) . Such an experiment could be planned in the e^+e^- collider *DAΦNE*, or by using quasi free $\bar{p}p$ annihilation in a suitable facility to produce slow ϕ mesons, as considered very recently by members of the GSI collaboration looking for meson-nuclear bound states [23]. For a ‘beam’ of ϕ mesons produced with momentum $p_L = 262$ MeV/c, it is then possible to inject strictly zero kinetic energy antikaons into a nuclear target by observing K^+ in the forward direction with the same momentum in the recoilless reaction denoted by (ϕ, K^+) . We defer a more detailed discussion of this reaction to a separate publication.

In conclusion, we have shown that ‘deeply bound’ kaonic atom states, i.e. states which are inaccessible via the X-ray cascade process, are sufficiently narrow to make them well resolved, particularly in l -selective reactions of the type mentioned above. The mechanism responsible for the suppression of widths in the presence of very strong absorptive potentials is the effective repulsion induced by such absorptivity. The net effect is repulsion regardless of the presence of strongly attractive real potentials and, in fact, the energy level spectra are dominated by the imaginary part of the potential. The calculated ‘deeply bound’ atomic spectra are remarkably insensitive to the model used for the potential or to the model used for the nuclear density, provided fits are made to the data on strong interaction effects in ‘normal’ kaonic atoms. Preliminary results suggest similar effects in antiprotonic atoms.

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REFERENCES

- [1] C.J. Batty, E. Friedman, A. Gal, Phys. Reports 287 (1997) 385.
- [2] T. Yamazaki et al., Z. Phys. A 355 (1996) 219.
- [3] T. Yamazaki et al., Phys. Lett. B 418 (1998) 246.
- [4] S. Hirenzaki, H. Toki, T. Yamazaki, Phys. Rev. C 44 (1991) 2472.
- [5] E. Friedman, G. Soff, J. Phys. G: Nucl. Phys. 11 (1985) L37.
- [6] H. Toki, T. Yamazaki, Phys. Lett. B 213 (1988) 129.
- [7] C.J. Batty, E. Friedman, A. Gal, Phys. Lett. B 335 (1994) 273.
- [8] C.J. Batty, E. Friedman, A. Gal, Prog. Theor. Phys. Suppl. 117 (1994) 227.
- [9] J. Mareš, E. Friedman, A. Gal, B.K. Jennings, Nucl. Phys. A 594 (1995) 311.
- [10] M. Alberg, E.M. Henley and L. Wilets, Ann. Phys. [NY] 96 (1976) 43.
- [11] M. Thies, Nucl. Phys. A 298 (1978) 344.
- [12] R. Brockmann, W. Weise and L. Tauscher, Nucl. Phys. A 308 (1978) 365.
- [13] M. Mizoguchi, S. Hirenzaki and H. Toki, Nucl. Phys. A 567 (1994) 893.
- [14] V. Koch, Phys. Lett. B 337 (1994) 7.
- [15] T. Waas, N. Kaiser and W. Weise, Phys. Lett. B 365 (1996) 12.
- [16] T. Waas, M. Rho and W. Weise, Nucl. Phys. A 617 (1997) 449.
- [17] M. Lutz, Phys. Lett. B 426 (1998) 12.
- [18] M. Krell, Phys. Rev. Lett. 26 (1971) 584.
- [19] E. Friedman, A. Gal, C.J. Batty, Phys. Lett. B 308 (1993) 6.
- [20] E. Friedman, A. Gal, C.J. Batty, Nucl. Phys. A 579 (1994) 518.
- [21] C.J. Batty, Nucl. Phys. A 372 (1981) 418.
- [22] A. Gal, E. Friedman, C.J. Batty, Nucl. Phys. A 606 (1996) 283.
- [23] A. Gillitzer, P. Kienle, T. Yamazaki (private communication).

FIGURES

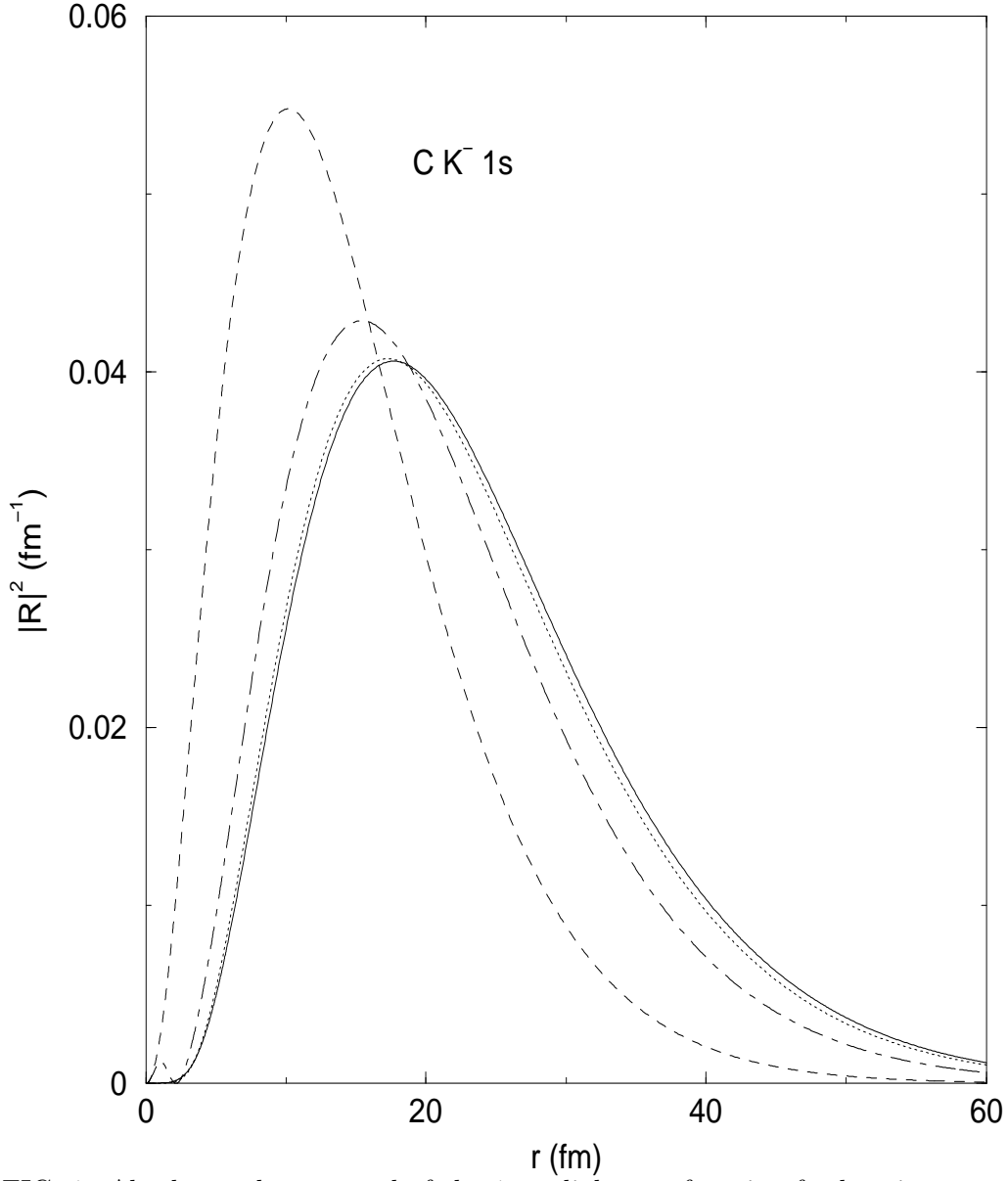


FIG. 1. Absolute value squared of the $1s$ radial wave function for kaonic atoms of C. Dashed curve for electromagnetic interaction only, solid curve with the full optical potential included, dotted curve for only the imaginary potential included and dashed dot curve for only the real optical potential included.

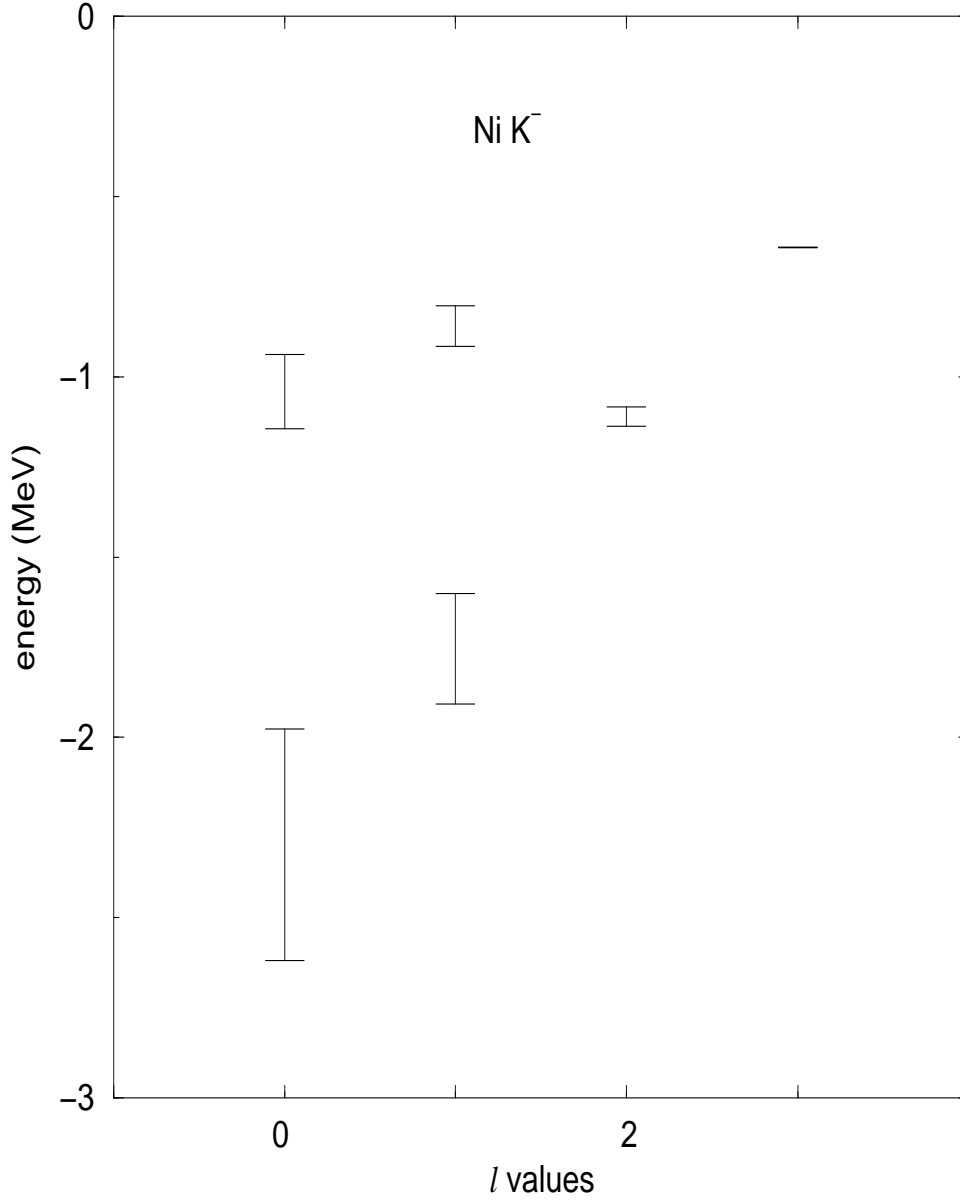


FIG. 2. Deeply bound levels in kaonic atoms of Ni calculated using the $t\rho$ potential specified in the text. The bars stand for the full width Γ ($=2 \text{ Im } B$) of the levels and the centers of the bars correspond to the energy ($-\text{Re } B$).

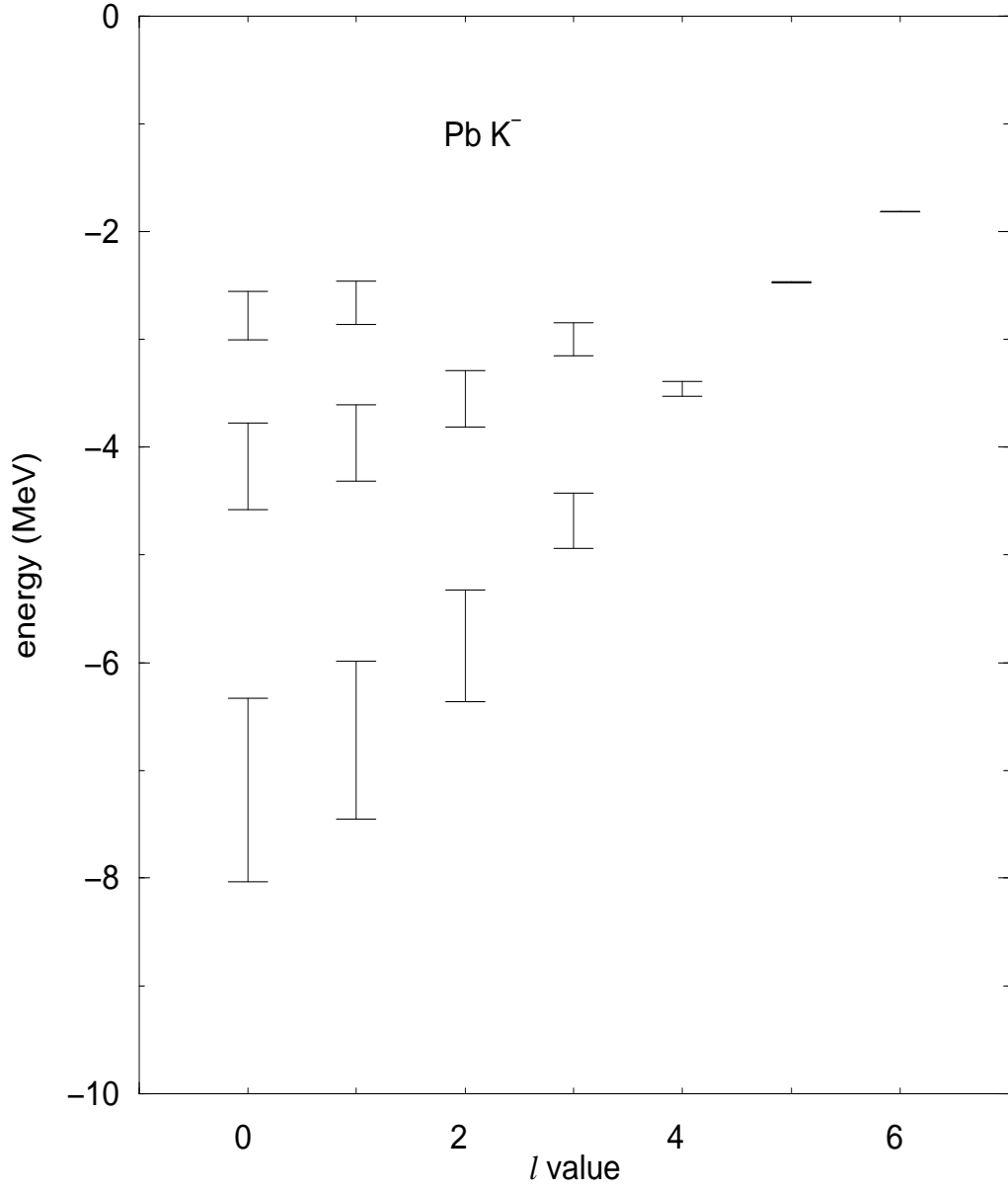


FIG. 3. Deeply bound levels in kaonic atoms of Pb (see caption of FIG. 2 for details).

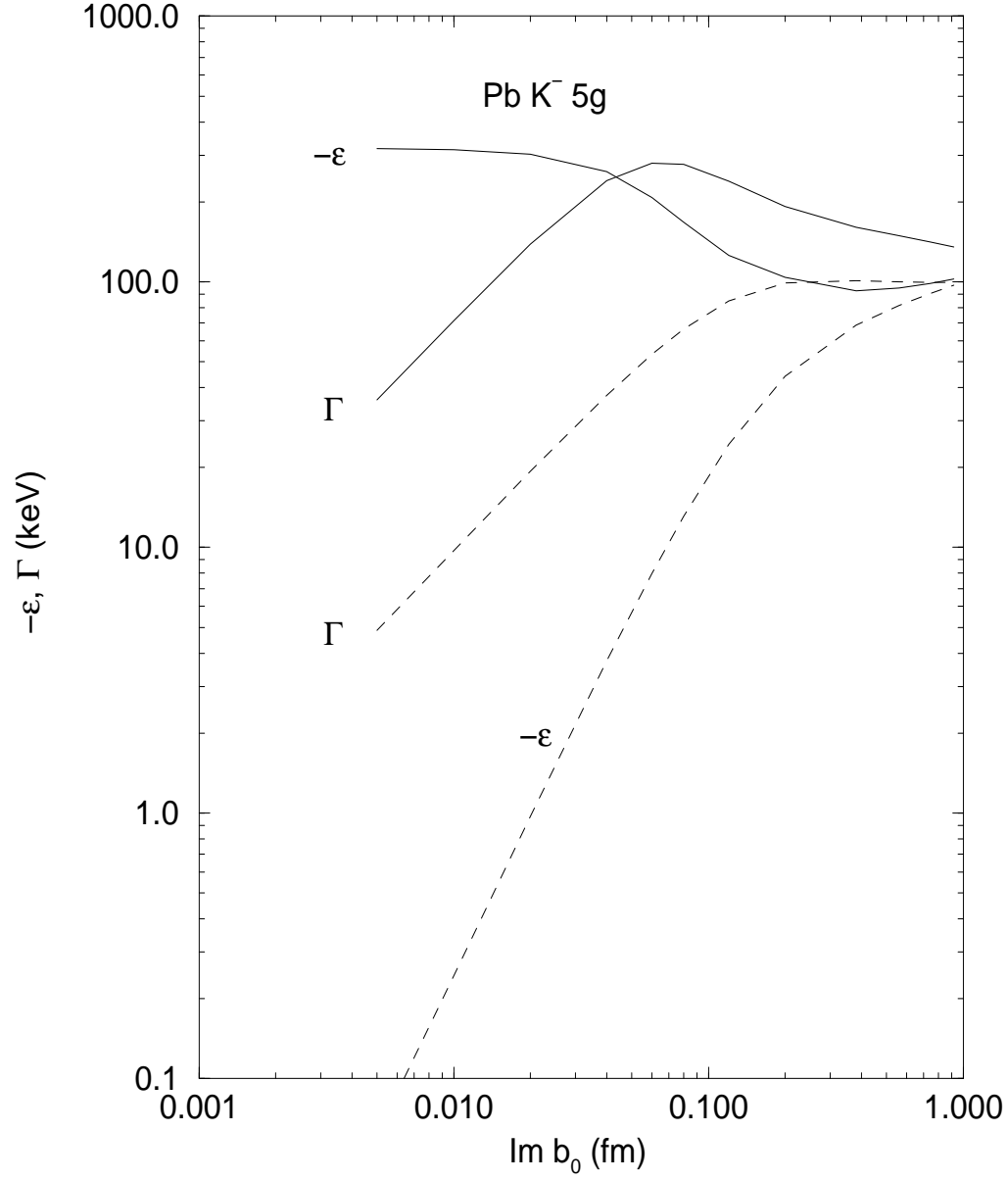


FIG. 4. Strong interaction shift and width for the $5g$ state in kaonic atoms of Pb as function of the imaginary part of b_0 . Solid curves for the full optical potential, dashed curves for imaginary potential only.